A Review of the Approach of NASA Projects to Planetary Protection Compliance

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Abstract—The approaches to planetary protection compliance by several space projects in the period between Galileo and the present are reviewed. The emphasis is on missions to Mars, based on the historical record and the specificity of planetary protection requirements for that planet. However, an interesting change in requirements dating back to Galileo's launch led many years later to the protection of Europa and the choice of ending the mission with an entry into Jupiter. An analogy exists for Cassini at Saturn, with the potential for protecting Titan from the orbiter (not the Huygens probe of course).

The Mars missions in the period include successes and failures. Planetary protection implementation is discussed for Mars Observer, Mars Pathfinder, Mars Global Surveyor, Mars Polar Lander, Mars Climate Orbiter, Mars Odyssey, and Mars Exploration Rover.

Next, some recent developments in planetary protection implementation for spacecraft being prepared for launch are presented. Finally, new planetary protection requirements adopted by COSPAR, which NASA is expected to follow, are described. [1,2,3]

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1. INTRODUCTION

NASA planetary protection, formerly planetary quarantine, is a set of regulations for extraterrestrial space missions which addresses applicable COSPAR resolutions, and ultimately derives from a 1967 United Nations treaty (the "Moon treaty"). The dual purpose of the NASA regulations is set forth in a basic policy, NPD 8020.7E [1]. The two objectives are: to protect extraterrestrial objects from terrestrial biological contamination that may interfere with the search for extant life, its remnants or its precursors; and to protect the Earth from the possible hazards of an extraterrestrial sample return.

The earliest history of planetary protection compliance by NASA space missions is the Lunar Ranger project, where the sterilization of the spacecraft was attempted. Soon a probabilistic approach to the likelihood of biological contamination was adopted by NASA and COSPAR. An allowable probability was established. In a later development, Sagan and Coleman provided a mathematical framework to evaluate missions for which contact was planned [2]. For flyby missions the probability was the probability of unintentional impact. For Mars orbiters in particular, a period of biological exploration was established, during which the probability of unintentional impact had to meet an upper limit requirement. (This is the so-called orbital lifetime requirement.) NASA established values for the various specific parameters needed to evaluate the Coleman-Sagan formula (perhaps the most well-known is the probability of growth) and for the specific probabilities of the requirements. The values of these parameters have been changed over the years that followed, always with a COSPAR concurrence.

The Apollo Project represents the first attempt to comply with the second purpose of the NASA policy, to protect the Earth. A serious effort was involved, which had two obvious aspects. The returned samples were returned in

[1] The reported work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

[3] IEEEAC paper #1485, Version 4, Updated November 23, 2004

Figure 1 President Nixon visits Apollo 11 crew in quarantine.
Photo courtesy of Johnson Space Center.

sealed containers to a confinement facility where they were examined for possible biological hazards in a planetary protection protocol [3]. In addition, the returning astronauts were taken to a planetary quarantine facility, where they stayed for 21 days (Fig. 1). However, the reentry vehicle was probably contaminated on its exterior by Moon dust from the lunar excursion module (LEM) during the LEM and command module docking. The reentry vehicle landed in the ocean. The reentry vehicle interior held Moon-contaminated space suits. The exterior of the sample containers was also likely contaminated by Moon dust. The astronauts walked across the deck of an aircraft carrier to enter the quarantine trailer. Hence if the Moon did pose a hazard to the Earth, the measures taken would not have been adequate. In fact a compromise between planetary protection and crew safety was struck. After the first two Apollo missions, the planetary protection protocol was deemed to show no hazard. The procedures were dropped; sample confinement on later missions was only for the protection of the sample from terrestrial contamination (not necessarily biological).

The Viking Project implemented the most comprehensive program of compliance with planetary protection requirements for a Mars mission. At the most fundamental level, the probability of (biological) contamination of Mars by all of the systems of each Viking spacecraft (lander and orbiter) and launch vehicle was not to exceed $1x10^{-4}$ [4, 5]. The project suballocated this allowable probability to various hardware systems and mission phases [5], as shown in Table 1.

The suballocation for the biological contamination of Mars by the lander was only $2x10^{-5}$. This lander suballocation had to include allowances for the possibility of recontamination of the lander during various mission phases, $0.6x10^{-5}$. Since the probability of contact with Mars was essentially one, the lander had to be sterile to a high degree of confidence prior to launch. The possibility of an incomplete sterilization had to be less than $1.4x10^{-5}$.

For the lander, a detailed microbiological assay procedure [6], a sampling plan, an approach for the estimation of the number of spores (burden) in each part of the hardware, and a scheme for the dry heat microbial reduction and control of burden at the subsystem level were adopted. Finally, a system was designed and built and a procedure for the dry heat microbial reduction of the lander in its aeroshell was employed. For the other spacecraft systems, various analyses were also developed and employed: the probability of impact, orbital lifetime, particle release from surfaces, etc. All of these methods form the basis for post-Viking mission planetary protection compliance.

However, Viking life detection findings were ruled to be negative, although not without some exciting controversy supplied by the Labeled Release biology experiment. After Viking and this null interpretation, the Space Science Board (now Space Studies Board) of the National Research Council produced recommendations for less stringent planetary protection requirements for future Mars missions [7]. NASA formally adopted a new structure for the planetary protection of other solar system objects and new requirements specifically for Mars in 1999 [8], and COSPAR also did so [9]. Although some further refinements for Mars were also adopted by COSPAR [9]

Table 1. Viking Project Allocation of Probability of Biological Contamination of Mars [5]

Contaminating Event	Mission phase	Flight subsystems	Probability of contamination allocation
Impact of Mars by unsterilized hardware	Injection, cruise, orbital ops	Upper stage, bioshield base, orbiter	$3.2x10^{-5}$
Biological contamination released from unsterilized hardware and transported to Mars	Cruise, orbital ops	Upper stage, bioshield base, orbiter	$2.8x10^{-5}$
Biological contamination of Mars by the lander	Landing, landed ops	Lander	
Recontamination of the lander	All flight phases prior to landing	Lander	$0.6x10^{-5}$
Probability lander not sterile	All post-sterilization	Lander	$1.4x10^{-5}$
Reserve	All	All	$2x10^{-5}$
Total			$1x10^{-4}$

and will be adopted by NASA in a revision of NPR 8020.12B[3] [8], this latter document represents the current NASA planetary protection requirements.

2. The Current NASA Outbound Planetary Protection Requirements for Mars

The current planetary protection requirements [8] for Mars include limits on the probability of impact of Mars P_I, limits on total bacterial spore burden N_{total} (on all surfaces, in joins and embedded in non-metallic materials), and limits on surface bacterial spore burden N_s. For any mission where the launch vehicle (or a stage thereof) may impact Mars, P_I for the launch vehicle must not exceed 10^{-4}. For any mission where the spacecraft may accidentally impact Mars (even during a gravitational assist), P_I for the spacecraft must not exceed 10^{-2}. For a Mars orbiter mission, either P_I must not exceed both 10^{-2} for 20 years after launch and 0.05 for the next thirty years or N_{total} must not exceed $5x10^5$ spores. For a Mars lander without life detection flight experiments, N_s must not exceed $3x10^5$ spores; for a Mars lander with life detection experiments, N_s must not exceed 30 spores.[4] For a Mars probe, N_{total} must not exceed $5x10^5$ spores. The lander burden requirements were established in direct response to the recommendations of the SSB [7].

[3] Formerly NPG 8020.12B

[4] The actual requirement in Reference 8 is as sterile as was a Viking lander after its terminal sterilization. The value of 30 spores is the current best estimate of that condition. However, that the 30 spores are a surface requirement (with no requirement on the mated and encapsulated burden) is this author's interpretation of the intent of the requirement. The point is almost moot if dry heat microbial reduction is employed.

3. The Methods of Planetary Protection for Mars

Probability of Impact Analysis

The probability of accidental impact P_I by a spacecraft (i.e., flyby, orbiter, unseparated lander, and even a lander) during the launch, injection and cruise phases of a mission is treated by:

$$P_I=\Sigma\, p_i\, q_{i+1}$$

where p_i is the *a priori* probability of impact due to the i^{th} maneuver and q_{i+1}s the probability that the next maneuver will not occur. The maneuver probability of impact p_i is calculated from the aim point and Mars position uncertainties and the execution (error) uncertainties. The historical (acceptable) value of the probability (of failure) q_{i+1} is 0.01. However, it is also acceptable to estimate q_{i+1} from spacecraft reliability. This method provides a value that depends on the duration between maneuvers in a logical manner. Reasonable failure rates based on several detailed reliability analyses have also been accepted. Formally, for the last maneuver, q is 1, because there are no more maneuvers.

For the upper stage of the launch vehicle, P_I has at most two terms, e.g., for launch and injection.

Compliance with the Mars orbiter probability of impact requirements may also include analyses of accidental impact during orbital insertion, aerobraking (if any), and orbital lifetime. The 20-year requirement includes P_I from the prior phases, of course. Aerobraking has been treated by a consideration of the probability of impact for each pass p_i, based on the navigation uncertainties (altitude), maneuver execution errors, and the variability of the Mars atmosphere

Figure 2 Swab sampling. Photo courtesy of Kennedy Space Center.

density at the intended pass altitude. For n drag passes, the probability of at least one failure (for a healthy spacecraft) is given by:

$$P_I = 1-(1- p_i)^n \quad (\approx n\, p_i \,, \text{if } p_i << 1)$$

In addition, since the aerobraking orbits typically do not have orbital lifetimes exceeding the balance of 20 years after launch, the probability of spacecraft failure (from its reliability) must be added. Note that although a slower conservative (high density margin) aerobraking phase may have a greatly reduced probability of impact due to a drag pass failure, eventually the probability of spacecraft failure will begin to dominate the probability of impact. Finally, the probability of loss of communications during critical orbital periods must also be added.

Orbit Lifetime Analysis for Mars

Orbital lifetime analysis (specifically the probability that the orbiter will not impact within the balance of 20 years, discounted by the time to reach Mars) uses atmospheric drag and standard orbital propagation methods. An atmospheric model at the altitudes of interest for the typical science or mapping orbit is required. Recently, such a model has been approved for this use [10]. The principal stochastic variable is the solar activity probabilities during the period of interest (because increased solar activity expands the atmosphere and increases the density at a given altitude.) The probability of spacecraft failure may also enter into the calculation because a healthy spacecraft with a propellant reserve may be raised to a higher, safer orbit at the end of its mission. For inadequate (low altitude) orbiters, the mission plan may have to include this periapsis raise maneuver to demonstrate compliance. Otherwise, the worst case drag coefficient based on orbiter attitude may be employed in the calculation. The probability that the science orbit's lifetime exceeds the balance of the 20 years but does not exceed the following 30 years must be analyzed also and bookkept in the so-called 50 year compliance analysis.

The same approach is taken for the period from 20 years to 50 years after launch. As noted above, the entire balance of the 50 years must be considered to treat a spacecraft failure early in the science orbit phase. However, for a duration this long, the sufficient approach of requiring each solar maximum (as many as five since the solar activity period is 11 years) to be equal and small enough to meet the probability requirement is extremely conservative. That is, the standard method overestimates the probability of inadequate lifetime for a given initial orbit or overestimates the required initial altitude required to meet a specified probability. In fact, a method that considers combinations of one larger solar maximum and three smaller maxima and two somewhat larger maxima and two smaller ones has been developed, published and employed [11 and 12]. This trinomial method eliminates some of the conservatism. However, it is labor intensive because it involves trial and error solutions with multiple orbital propagation runs.

Surface Spore Burden Estimation

The general approach to establishing the surface burden on a Mars lander is the NASA standard microbiological assay, as it was for the Viking Project. This procedure involves sampling the surfaces of the hardware with sterile swabs and/or wipes, dampened with sterile water (Fig. 2). The area sampled is approximately controlled (e.g., 25 cm^2 for a swab sample). Sonication in sterile water is employed to separate the microbes from particles and to break up clumps of microbes to form a suspension of free single microbes. The samples are then heat shocked (80C for 20 minutes).[5] This process is intended to kill all microbes except spores. The survivors are the planetary protection operational definition of spores.[6] Then the suspension in poured into

[5] The Viking Project split the samples and also assayed half of them without any heat shock. Thus the total of spores and vegetatives were also counted.

[6] This is not the microbiological definition of a spore. Here some heat resistant microbes in the vegetative form that survive the heat shock are also counted (as spores).

tripticase soy agar (TSA) plates and incubated at 32C for three days.[7] Finally the visible colonies are counted and added to yield an estimate of the number of spores n in the original sample (all of the swabs and wipes) from a known total surface area A_s.

The statistical treatment includes the calculation of the mean spore burden density, n/A_s, and a 3-sigma worst case value, $(n + 3\sqrt{n})/A_s$. The area variance is neglected. A special treatment for the case where n is zero or one from the set of swabs (only), based on Poisson statistics, is used. The worst-case spore burden density is $(n + 3)/\sqrt{(A_s A_0)}$, where A_0 is the surface area to be represented by the sample.

A comprehensive sampling plan provides for the sampling of each surface to occur at last access to the surface[8] and an appropriate fraction of the surface represented A_0 to be sampled A_s (15% is typical). The worst case surface spore burden N_s is then calculated as the total of the products of the worst case burden densities with their corresponding represented areas. Surfaces inside sealed enclosures, inside enclosures vented through HEPA filters, and surfaces inside a vented enclosure that is in turn inside another vented enclosure do not add to the estimate. There are also planetary protection specifications for surface spore burden densities [8] based on the level of contamination control that a surface sees (e.g., class 100, 000 cleanroom) that may be used instead of an assay. However, these values are of necessity very conservative. They are best used for surfaces that cannot be sampled.

Surface Burden Reduction

For a Mars lander, the worst-case surface spore burden may be reduced by several methods. For all other accountable surfaces, cleaning and microbial reduction processes may be applied at the project's option. However, with one exception, the reduction must be verified with an assay. Thus sterile alcohol wiping may be used either before any assay or after an assay with poor results, but in the latter case a second assay is needed. The only exception is dry heat microbial reduction (DHMR), for which there are planetary protection process specifications [8]. The process involves temperatures in the range of 104 to 125C with controlled absolute humidity, for durations that depend on the temperature. DHMR is particularly useful for large areas like honeycomb composite structures, parachutes, thermal blankets and air bags. It may be used without any assay and with the surface spore burden density specifications or with a prior assay to establish a lower pre-treatment density. Protection against recontamination is essential. Rework of the hardware also typically invalidates prior reduction processes.

As of this writing, no NASA Mars lander mission with life detection experiments has been flown since Viking. The Viking planetary protection implementation has been described above.

Total Spore Burden Estimation

For a Mars orbiter with inadequate lifetime or a Mars probe, the total spore burden must be estimated to comply with the requirement on N_{total}. Here with very few exceptions the lack of an approved method to assay the spores encapsulated in the bulk of non-metallic materials compels the use of the planetary protection specifications for the spore volume density [8]. Of course DHMR may be employed to good effect. No recontamination is possible. Otherwise the procedure for the spore burden estimate is analogous to that for a lander.

Finally, a few special precedents, which are not contained in the NASA regulations [8], have been established on recent Mars missions. Approval of these exceptions must be requested by way of the project's Planetary Protection Plan. The planetary protection specification "Time-Temperature for Sterility" [8], which states that 500C or more for 0.5 seconds or more is sufficient to sterilize terrestrial microbes, has been used in conjunction with Mars entry heating analyses to eliminate from total spore burden accounting most of the cruise stages of Mars Pathfinder (MPF), Mars Polar Lander (MPL) and Mars Exploration Rover (MER). In addition the surfaces of the entire MPF aeroshell, the MPL heat shield, and the MER heat shield were also eliminated by this approach. Recently, the Mars Reconnaissance Orbiter (MRO) gained approval for an analysis that combines break-up and entry heating to eliminate most of its total spore burden. This extremely detailed analysis is being used to meet the 5×10^5 total spore requirement because the MRO science mapping orbit is far too low to meet the 20-year probability of impact requirement with any feasible system reliability to perform a periapsis raise at the end of the science phase.

The impacting hardware of MPL and MER have been permitted to use the part of the allowed mission total 5×10^5 spores which was not taken up by the 3×10^5 spores allowed on the lander accountable surfaces. This 2×10^5 total spore allowance was applied to the bulk non-metallic materials and the interior surfaces of the honeycomb composite structures of the aeroshells, and the MER electronics modules located on the backshell. These sources of spores would likely be released upon impact with the surface of Mars and possibly from the backshell being dragged around by the parachute. In retrospect, this

[7] In practice counts are made at one and two days also, to detect surfaces that may require remediation (cleaning).

[8] Planetary protection requires the protection of the surface against subsequent recontamination, which would invalidate the estimate.

Table 2. NASA Planetary Protection Categories

Category	Mission Type	Target & Encountered Solar System Bodies
I	any	Sun, Mercury, and Moon
II	any	All but Mars, Europa, Sun, Mercury, and Moon
III	Orbiter, flyby	Mars, Europa
IV A	Lander without life detection	Mars, Europa
IV B	Lander with life detection	Mars, Europa
IV C	Lander in special region	Mars, Europa
V U	Sample return from unrestricted body	Case by case (examples are Genesis and Stardust)
V R	Sample return from restricted body	Mars and by default all, until ruled on case by case

saved the MPF planetary protection compliance, where these sources were overlooked (i.e., considered non-accountable). The $2x10^5$ spore allowance was used for a small number of spores in the MPF cruise stage that were thought to possibly not reach 500C during the entry heating.

4. Expected Revisions to NASA Planetary Protection Regulations for Mars

The principal revision expected in NPR 8020.12C is the addition of a third category of Mars lander, which investigates "special regions" of Mars. (See Table 2 above.[9]) The definition of a "special region" is concerned with features on the surface or at depth which may contain water. Such a lander must meet the requirements of a lander with life detection experiments. If the landing occurs in a "special region", its surface burden may not exceed 30 spores. If only a part of the lander system reaches the "special region", as an option, the requirement may be applied only to that part, but its cleanliness must be protected from the rest of the lander. This new category has already been adopted by COSPAR [9]. Likely, the Phoenix project will be the first NASA mission in this category.

5. Planetary Protection for Other Solar System Bodies

The present NASA planetary protection regulations [8] exempt lunar missions. After the first few Apollo missions, the judgment was made that the Moon did not need any protection and that the Earth needed no protection for samples returned from the Moon. However, it is reasonable to protect the Moon from extraterrestrial samples. The new NPR 8020.12C is expected to include the Moon in the category for which a formal request for relief from further planetary protection requirements is the only requirement. This is the current status of the Sun and Mercury.

Missions to Europa will likely receive significantly more stringent requirements based on the widely accepted existence of a liquid water ocean beneath its ice crust. Recommended requirements have already been published [13].[10] Obviously there is no history of planetary protection implementation to report.

While the other solar system bodies not explicitly noted have only minor implementation requirements, a precedent was established during the pre-launch negotiations for Galileo planetary protection, relative to the unpredictability of the final orbit after the orbiter died. The compromise reached called for the Galileo project to report during the period of scientific observations any findings that would enhance the biological interest in Jupiter or any of its satellites. The NASA Planetary Protection Officer would then oblige the project to undertake measures to avoid an impact with any objects so ruled by him. Galileo project clearly found evidence that Europa is very biologically interesting. It is this agreement that led to the project targeting the Galileo orbiter at the end of its mission into Jupiter, to absolutely avoid an impact with Europa. The analogous clause is also found in the Planetary Protection Plan of the Cassini mission to Saturn (e.g., for conditional avoidance of Titan or another satellite) and in the DAWN Project to the asteroid Ceres.

6. Planetary Protection for Sample Return Missions

Current NASA planetary protection regulations characterize extraterrestrial sample return missions as either "unrestricted Earth return" or "restricted Earth return." For "unrestricted Earth return" missions, so approved by the NASA Associate Administrator for

[9] Based on the expected new NASA regulations, as discussed.

[10] Already adopted by COSPAR [9]

Figure 3 MPF on Mars by Sojourner camera, showing the integrated subsystem assembly (ISA)

Science, the planetary protection requirements and implementation are those of the mission if there were no sample return. Recommended guidelines for the characterization of sample return missions from small solar system bodies (asteroids, comets and certain planetary satellites) have been published [14].[11] Two NASA "unrestricted Earth return" missions have been launched. Since Genesis contacted no solar system body, it had no forward planetary protection implementation, either. Stardust, for which the target was a comet, had merely to provide simple project planetary protection documentation and to avoid any accidental impacts of the comet (by the spacecraft or the launch vehicle).

The planetary protection implementation of a "restricted Earth return" mission (e.g., Mars or Europa) would involve spacecraft system sterilization and either the absolute containment or sterilization of the sample and any hardware which contacts the target body. Recommendations for requirements for a Mars sample return mission have been published [15], but the regulations provide few details. The Mars Sample Handling Facility has also been considered [16]. However, no "restricted Earth return" mission has yet been conducted.

7. SUMMARY

The following Mars landers have all successfully complied with the NASA planetary protection requirements as generally presented and by the methods described in this report: MPF, MPL, and MER. Only a description of MPF's planetary protection is available in a public journal [17]. MPF employed a HEPA filter to isolate the entire central electronics assembly of the lander (Fig. 3). The parachute and the thermal blankets were all dry heat microbially reduced. The net result was a surface spore burden worst-case estimate of only $3x10^4$ spores. MPL did not have the advantage of a bus electronics enclosure. Mainly for this reason, MPL's spore estimate was a little less than $3x10^5$ spores, just below the requirement. MER made extensive use of DHMR by plan. Also by plan, HEPA filters were installed both on small separate electronics modules (Fig. 4) and, analogously to MPF, on the central electronics unit of the rovers. Although a much larger spacecraft than MPF, the estimate of the launch value for MER was only $1x10^5$ spores. Unfortunately, another $1x10^5$ spores had to be carried for recontamination of the aeroshell's backshell during launch from an uncharacteristically contaminated launch vehicle fairing interior. (The backshell was not expected to reach 500C during Mars atmosphere entry.)

The following Mars orbiters have all successfully complied with the NASA planetary protection requirements as generally presented and by the methods described in this report: MGS, MCO and Odyssey. Of course MGS and Odyssey are still operational.

Future missions are beyond the scope of this report. Mars landers to special regions or with life detection experiments do present a challenge. A system-level sterilization as was done for Viking doesn't seem feasible with modern electronics and packaging. Other approaches are being studied, including a sterile rover isolated from a lander cleaned only to the category IV A level [18]. A Europa mission, which may require true sterility, may actually have to be sterilizable at the system level. Credit for the Jupiter radiation environment is also being considered. Finally, a significant development program is needed to comply with the planetary protection requirements for Mars sample return or other "restricted Earth return" missions. This program has begun [19].

[11] Again, already adopted by COSPAR [9]

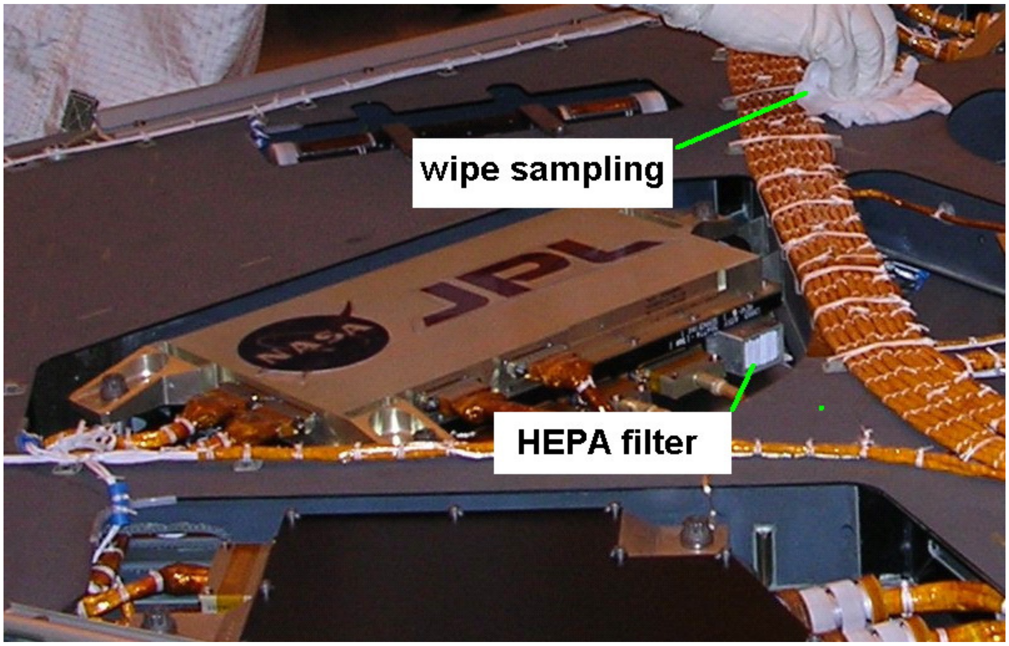

Figure 4 MER Power Lander Electronics Module (PLEM), showing HEPA filter. A wipe sample of the lander structure is also visible. Photo courtesy of the Jet Propulsion Laboratory.

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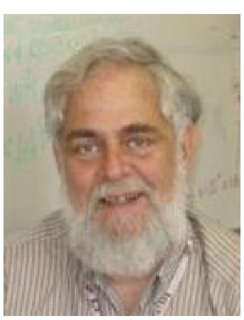
BIOGRAPHY



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